RE-EVALUATION OF THE UNCERTAINTIES FOR THE NIST CALIBRATION SERVICES FOR AC-DC DIFFERENCE OF VOLTAGE

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Abstract - This document provides a summary of the various contributions to the uncertainties offered in the NIST calibration service for ac-dc difference of thermal converters. Individual contributions are listed and their origins briefly described. These individual uncertainties have been estimated using the square root of the sum of the squares (RSS) method as described in "Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results" [1].

1. Introduction

This NIST calibration service covers ac-dc thermal transfer instruments at voltages from 250 mV to 1000 V, for frequencies from 10 Hz to 1 MHz. The overall uncertainties for this service have been extensively documented in the past, [3, 4, 5, 6, 7] and recently, newly revised uncertainties for voltage converters at 10 Hz and current converters and transfer shunts at 100 kHz have been published [4,5] following the guidelines in [1]. This Technical Note provides an up to date derivation following the current guidelines for the remaining uncertainties associated with this calibration service for thermal voltage converters. All ac-dc difference uncertainties reported in this document are given in microvolts per volt (μV/V) of applied voltage. The components of the uncertainty evaluated by statistical means, designated Type A components, will be referred to as Type A uncertainties in this document. For those elements in the uncertainty tables estimated from rectangular distributions with limits ±b (Type B components of the uncertainty), the entries in the tables are the equivalent standard deviations of that distribution, equal to $b/\sqrt{3}$. These are referred to as Type B uncertainties in this document.

The calibration service for ac-dc difference of thermal converters relies on multijunction thermal converters (MJTCs) as the primary standards and on various thermal voltage converters (TVCs) and thermoelements (TEs) as the reference and working standards [2,3]. Calibrations are performed by comparing the ac-dc difference of a customer's thermal converter to the ac-dc difference of a NIST standard TVC by connecting the two TVCs in parallel.

TVCs are usually constructed of TEs with range resistors in series with the heaters. For single range TVCs, the range resistor may be mounted in a separate shielded enclosure with an intervening connector, or it may be mounted in the same enclosure as the TE. For multirange TVCs, the range resistors are switch selected. A TVC may also consist of just a TE with no range resistor for the lower voltage ranges. The analyses of the uncertainties given below include contributions for these and other structural characteristics.

Due to the natural division between the hardware and methods used for the frequencies up through 100 kHz and for frequencies above 100 kHz up to 1 MHz, the uncertainties have been separated into two such groups also. For convenience, the uncertainty analyses for thermal converter calibrations are located in Appendices A through F.

2. Primary Standards

The NIST primary standards for ac-dc difference are a group of multijunction thermal converters of different designs and from different manufacturers [2]. Theoretical analysis and measurement results indicate that the ac-dc differences of these devices are very close to zero as both voltage and current converters at frequencies from a few tens of hertz to about 10 kHz. The uncertainties associated with the intercomparison of the primary standards have been evaluated by Hermach [6]. From that analysis, the uncertainty assigned to the group of primary standards from 2 V to 10 V from 30 Hz to 10 kHz (for a coverage factor of k = 1) is 0.27 μV/V as shown in Table A.1.

3. Characterization Method

In addition to the primary standards, the other thermal transfer standards on which the ac-dc difference calibration services are based are classified as either reference or working standards. The reference and working standards are characterized in terms of the primary standards using the process shown in the diagram in Figure 1. To extend the upper frequency range, special TVCs [11] with ac-dc differences nearly independent of frequency from 10 kHz to 1 MHz are characterized in terms of the primary standards at 1 kHz. The nearly flat frequency response of the special converters is used to determine the ac-dc differences of the reference and working standards up to 1 MHz. To extend the lower frequency range, selected thermoelements are assembled in cluster modules and operated at low heater temperatures in order to minimize low frequency error due to the failure of the TEs to thermally average the signal [4]. The reference and working sets of TVCs are constructed to have ac-dc differences nearly independent of voltage level and are characterized over the whole voltage calibration range by range-to-range build-up and build-down comparisons. The uncertainty analysis for the extension to frequencies higher than 1 kHz is presented in Table A.2. The uncertainty analysis for the frequency extension to 10 Hz is presented in

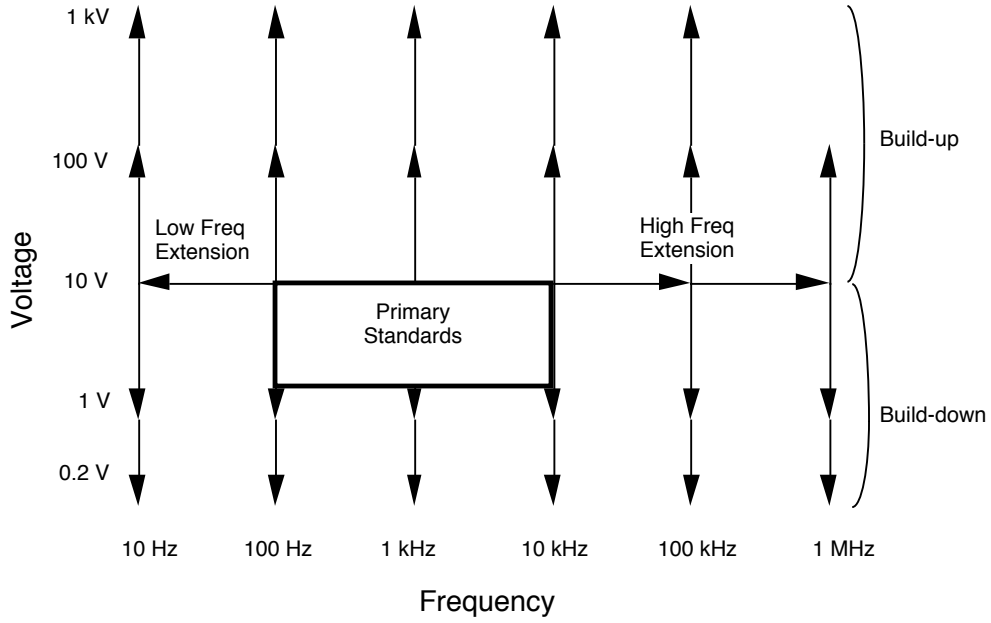

Fig. 1. Diagram of the primary standards, high and low frequency extension paths and build-up and build-down paths used to characterize standards over entire parameter space.

[4].

4. Reference Standards

The reference standards have generally been found to have superior characteristics either due to construction or by selection and are not used for routine day-to-day calibrations. The voltage reference standards are a set of coaxial, single-junction thermal converters (SJTCs) and range resistors that have full-scale ranges from 0.6 V to 500 V at frequencies from 10 Hz to 100 kHz [8]. This reference set is identified as the F_1 set of TVC. The ranges at and below the 10 V range of the reference set are compared to the primary standards at 1 kHz to determine their ac-dc differences. The uncertainty components for this measurement are shown in Table A.1, and include the pooled standard deviation of the measurements as well as Type B uncertainties for the TVCs and the MJTC comparator system [2]. The Type B uncertainty elements for the MJTC comparator system include allowances for the following error sources:

- the voltmeter used as the detector,
- the determination of the response characteristic of the standard TVC,
- errors in the circuitry that compensates for the response characteristic,
- dc reversal error, and
- ac effects in the comparator, including electromagnetic interference.

Build-up and build-down measurements are made within the F_1 set to evaluate the ac-dc differences up to 500 V and down to 0.5 V, as shown in Tables A.3a and A.3b (1 kHz) through A.7a and A.7b (100 kHz) of Appendix A. Each step in the build-up or build-down process has an associated uncertainty determined by the square root of the sum of the squares (RSS) of the uncertainty of the previous step and the uncertainties in the measurement process at that level. A diagram of the method used to determine the values for the reference standards is shown in Figure 2.

At voltages up to 200 V, the Type B uncertainties are dominated by the contribution of the lower voltage TVC. Above 200 V, however, the uncertainties include additional elements which depend on the electrical and mechanical characteristics of the high-voltage resistor and its mounting. These may include changes in the dielectric loss of the resistor structure and changes in the capacitance between the resistor and internal shield and are usually caused by self-heating of the resistor.

Due to voltage limitations of the MJTC comparator, a different comparator system [9] was used at the 200 V level and above, and the increase in the Type B uncertainty component for this system is given for the appropriate voltages in Tables A.3a and A.3b through A.7a and A.7b. The contributions to this component include:

- detector accuracy,
- the determination of the response characteristic of the standard TVC, and
- ac effects in the comparator, including electromagnetic interference.

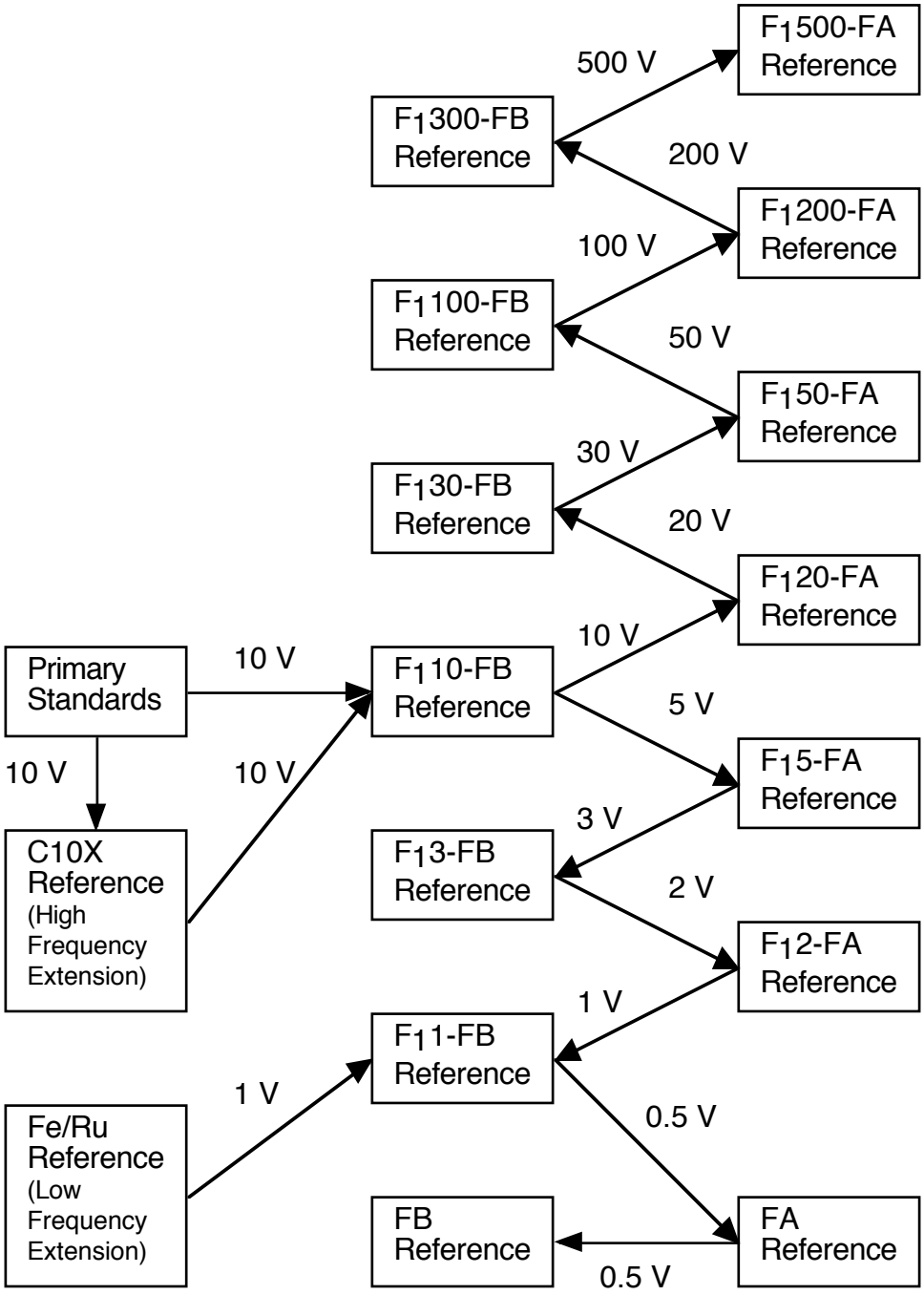

Figure 2. Diagram for the determination of the values of the NIST reference standards, beginning with measurements against the primary standards and showing the build-up and build-down chain.

5. Uncertainties for Automated Comparator

Measurements to characterize the working standard TVCs are generally made on an automated comparator system [10]; the attendant Type B uncertainties for this system are included in all the tables for each type of thermal transfer standard calibrated at NIST. These elements include:

- noise, linearity, and uncertainty in the digital nanovoltmeters used as detectors,
- stability of the signal sources, and
- electromagnetic pickup and interference in the system, including the detector leads.

Although the nanovoltmeters are used in their autoranging mode, the output emfs of the test and standard TVCs are generally appropriate for the 30 mV input range. The uncertainty element for these detectors is therefore independent of the voltage and frequency of the signal being applied to the converters. The stabilities of the ac and dc signal sources make more important uncertainty contributions than their absolute accuracies because the same voltage is applied to both TVCs, and therefore variations in the supplies from nominal voltage partially cancel out. The uncertainty analysis also reflects the fact that the signal sources are generally more stable at low and moderate voltages than at high voltages.

6. Uncertainties for Working Standards

Ac-dc differences for the NIST working standard TVCs [9] are determined by two methods. They are compared directly to the reference standards at voltages from 1 V (the lowest working standard voltage) up to 500 V on a 600 V range, at frequencies from 10 Hz to 100 kHz. These uncertainties are given in Appendix B. The working standards are also measured against the primary MJTCs, from 3 V to 10 V, in the frequency range from 30 Hz to 10 kHz. Following the comparison against the reference standards, a build-up of working standards from 1 V to 1000 V is performed. The values from the build-up path and from the direct comparison against the reference standards are averaged to determine the corrections for the working standards. The values obtained from the build-up at 3 V, 6 V, and 10 V, are compared to values determined from direct comparison to the primary standards from 100 Hz to 10 kHz.

The comparator system used for both the comparison to the primary and reference standards, and the build-up is that used for the determination of the reference standards, with identical Type B uncertainty components. For the direct comparison of the working TVC set to the reference TVC set, the uncertainty elements listed in Appendix B include:

- voltage level dependence,
- self-heating effects
- ac effects including bead error and the effect from stray capacitances.

The uncertainty elements applicable to the build-up process, listed in Appendix C, include the same effects and dependencies

For build-up measurements, the voltage level dependence may be significantly larger than for direct comparisons at the same voltage, particularly at high voltages. This is reflected in the tables in Appendix C. However, because the working standards are generally used at or near their rated voltages for customer calibrations, the level dependence is negligible for frequencies above about 40 Hz, where low-frequency errors may be significant. The uncertainties from self-heating and stray capacitances are also quite small at lower frequencies.

The working set resistors are designed to be used with thermoelements of two current ratings (2.5 mA and 5 mA) to provide two voltage ranges using the same resistor. For some ranges (for example, 10 V and 20 V) this precludes a direct build-up measurement between adjacent voltage ranges. In these cases, an intermediate TVC was used in the build-up, providing voltage steps of 10 V to 12 V to 20 V.

Since two independent build-up and build-down measurement paths are averaged together in these determinations, the uncertainty components associated with these procedures are combined as

$$u_c = \frac{1}{N}\sqrt{\sum_{n=1}^{N} \sigma_n^2} \qquad (1)$$

where:

u_c is the uncertainty at a particular voltage and frequency,
N is the number of paths, two in this case, used to determine the value of the TVC, and
σ_n is the standard error of the nth step in the measurement path, and
the ac-dc difference of the TVC at this voltage and frequency is the average of the ac-dc difference determined by the build-up paths.

This combined uncertainty for the working standards is given in Table C.6.

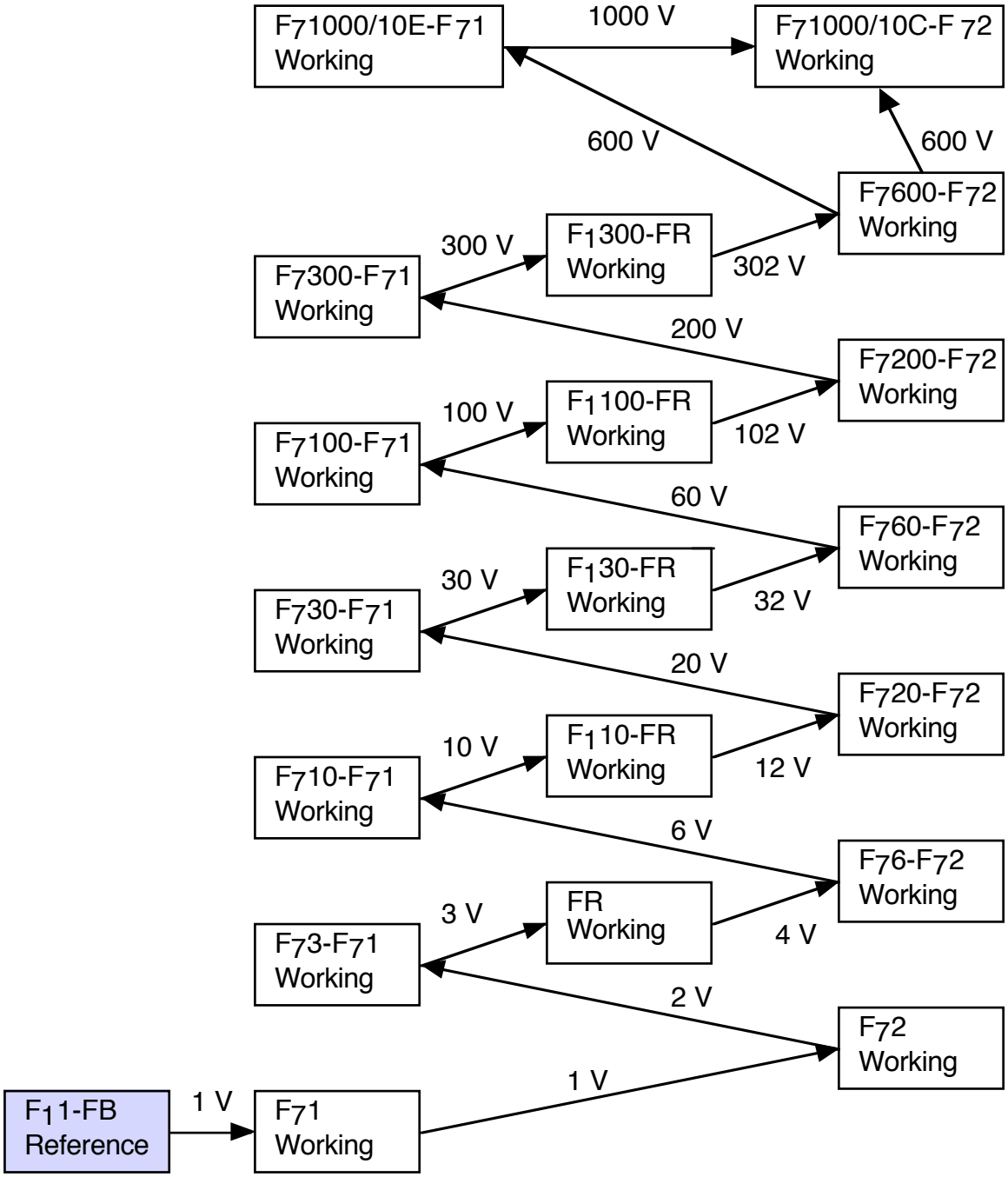

Figure 3. Build-up diagram for the NIST working standards, beginning with the comparison to the 1 V reference standard.

7. Uncertainties for Customer TVCs

Thermal voltage converters sent to NIST for calibration fall into three general categories – coaxial TVCs, conventional multirange TVCs, and multirange units having a solid-state circuit element, such as a transistor, as a thermal sensor. A diagram of the method for determining the values of the working standards, including comparison with the reference TVCs and build-up paths, is shown in Figure 3.

The pooled standard deviations included in these tables represent typical standard deviations for the instruments described. The uncertainties assigned to a customer's instrument, as shown in the tables, are based on this typical uncertainty. For actual calibrations, the uncertainties assigned to customer's instruments are based on the actual measurement uncertainties, and may be larger than the assigned uncertainties.

Coaxial TVCs
In the first category are the coaxial TVCs that are devices similar to the NIST reference and working standards. They contain a conventional thermoelement (or two, wired back-to-back to reduce dc reversal error) and multiplying range resistors in the same module as the TE, or in a plug-on module. The Type B uncertainties for coaxial TVCs are shown combined with the Type A components in Appendix D (Tables D.1 through D.5.) While in general these uncertainties are similar to those for the NIST working TVCs, their magnitudes are different. For example, characterization of a customer's TVC is at a specific voltage, so the uncertainty due to voltage level dependence is smaller. Moreover, the NIST working standard 1000 V resistor uses a 2.5 mA TE and consequently dissipates about 2.5 W, whereas a commercial 1000 V TVC may dissipate some 8.3 W, so the self-heating effects for these devices can be larger. The Type B uncertainty assigned to self-heating is consequently larger.

Multirange TVCs using conventional thermoelements
In the second category are the conventional multirange TVCs that have range resistors mounted on a switch, with one or more standard TEs mounted in the same package as the range switch. These devices also typically include potentiometers and/or meters, and allow the user to make an ac-dc transfer measurement using the electronics in the TVC instrument. To measure the ac-dc difference of these devices at NIST, the internal circuitry is bypassed and only the contribution to the ac-dc difference from the resistors and TE examined. The uncertainties for this category of customer's instrument are given in Appendix D.

Multirange TVCs with Solid-State Circuit Elements as Thermal Sensors
In the third category are the multirange units having a thermal transfer element using a solid-state circuit element, such as a transistor, as a thermal sensor. This instrument may also include input buffer amplifiers and protection electronics. A separate, high voltage range resistor is typically provided in a separate module. Owing to the extremely short time constant of the solid-state converter, the buffered output of the converter is averaged to obtain a useful signal. Even though the output signal is averaged at low frequency, the lack of thermal averaging in the heater remains a source of error, so the uncertainty is somewhat larger than for the other categories of transfer standards at frequency below about 100 Hz. The uncertainties for this category of customer's instrument are given in Appendix D.

8. Uncertainties for Frequencies above 100 kHz

The method to extend the characterization of thermal voltage converters from 100 kHz to 1 MHz is basically the same as that used from 10 kHz to 100 kHz; however, the apparatus is different, therefore the factors contributing to the uncertainties are different [7, 11]. For this frequency regime, special 5 V to 20 V TVCs were fabricated that are suitable for transmission line analysis, and whose construction minimizes some errors and makes other errors predictable. The converters contain series resistors and UHF-type thermoelements mounted in cylinders, and are made of non-magnetic materials. The series resistors are carbon coated ceramic rods with their original magnetic end caps replaced with non-magnetic caps. The transmission line analysis is divided into three parts: the voltage standing wave for the input connector, the transimpedance of the resistor, and current standing wave in the region of the thermoelement.

Appendix E contains the uncertainty contributions for the specially constructed 5 V to 20 V TVCs. The uncertainty elements include: the uncertainty of the primary standards, stability of lower frequency TVCs, comparator system for lower frequency measurements, low frequency voltage steps, thermoelement as current comparator, transimpedance of resistor, current standing wave, tee and connector voltage standing wave, connector reproducibility, lower frequency extension, skin effect, and high frequency comparator system.

Although the standard deviations vary somewhat between the coaxial and multirange TVCs, the final expanded uncertainties in this frequency range are dominated by the uncertainties for the characterization of the NIST standards. Therefore, there are no differences in the calibration uncertainties for the various types of TVCs. The uncertainties provided to customers for this category of instrument are given in Appendix F.

9. Summary

Appendix G provides a summary of the assigned uncertainties for the NIST calibration service for ac-dc difference from 10 Hz to 1 MHz, and from 0.5 V to 1000 V. Information on the determination of the uncertainties listed in these tables for the various classes of customer' standards are given in this document as well as in [4] and in [7].

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Appendix A. Uncertainties For Primary Standards And Reference Standards

Table A.1. Uncertainty for 10-V reference standard measured against the MJTC primary standards at 1 kHz. In this table, S_p is the pooled standard deviation of the measurements, $u_{comparator}$ is the uncertainty of the comparator system, $u_{reference}$ is the uncertainty of the reference TVC, $u_{primary}$ is the uncertainty of the primary standard, u_c the combined (k = 1) uncertainty, and U the expanded (k = 2) uncertainty. S_p is a Type A uncertainty; the other uncertainty components are Type B. All ac-dc difference uncertainties are given in μV/V.

S_p	$u_{comparator}$	$u_{reference}$	$u_{primary}$	u_c	U
0.29	0.10	0.12	0.27	0.42	0.84

Table A.2. Uncertainties, given in μV/V, for the frequency extension from 1 kHz to 100 kHz for the F_1 reference TVC at 10 V, based on measurements against the primary standards. In this table, $u_{extension}$ represents the uncertainty element for the frequency extension.

Frequency	S_p	$u_{primary}$	$u_{extension}$	$u_{comparator}$	$u_{reference}$	u_c	U
10 kHz	0.29	0.27	0.23	0.10	0.23	0.54	1.08
20 kHz	0.29	0.27	0.29	0.10	0.23	0.60	1.20
50 kHz	0.29	0.27	0.72	0.10	0.40	0.95	1.90
100 kHz	0.29	0.27	1.15	0.10	0.58	1.38	2.76

Table A.3a. Uncertainties, given in μV/V, for the reference TVC build-down at each step from 10 V to 0.5 V at 1 kHz. In this table u_{TVC} refers to the Type B uncertainty of the TVCs.

Voltage Step[1]	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 5 V	0.47	0.10	0.12	0.42	0.65	1.30
5 V to 3 V	0.47	0.10	0.12	0.42	0.82	1.64
3 V to 2 V	0.47	0.10	0.12	0.42	0.95	1.90
2 V to 1 V	0.47	0.10	0.12	0.42	1.07	2.14
1 V to 0.5 V	0.47	0.10	0.12	0.42	1.18	2.36

Table A.3b. Uncertainties, given in μV/V, for the reference TVC build-up at each step from 10 V to 500 V at 1 kHz.

Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 20 V	0.47	0.10	0.12	0.42	0.65	1.30
20 V to 30 V	0.47	0.10	0.12	0.42	0.82	1.64
30 V to 50 V	0.47	0.10	0.12	0.42	0.95	1.90
50 V to 100 V	0.47	0.10	0.12	0.42	1.07	2.14
100 V to 200 V	1.71	0.58	0.42	0.42	2.14	4.28
200 V to 300 V	1.71	0.58	0.42	0.42	2.83	5.66
300 V to 500 V	1.71	0.58	0.42	0.42	3.39	6.78

[1] The uncertainty determined for each step in the build-up or build-down process is calculated by the RSS combination of the uncertainty from the previous step, and the Type A and Type B components of the uncertainty for the measurement of the voltage step being determined. For example, the combined uncertainty for the voltage step from 5 V to 3 V is calculated as:

$u_{5Vto3Vstep} = \left(S_0^2 + u_{comparator}^2 + u_{TVC}^2 + u_{10Vto5Vstep}^2\right)^{1/2}$ or $u_{5Vto3Vstep} = \left(0.47^2 + 0.10^2 + 0.12^2 + 0.65^2\right)^{1/2} = 0.82\ \mu V/V$.

Note that $u_{reference}$ for each step is included in the uncertainty component from the previous step.

Table A.4a. Uncertainties, given in μV/V, for the reference TVC build-down at each step from 10 V to 0.5 V at 10 kHz.

Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 5 V	0.50	0.10	0.12	0.54	0.75	1.50
5 V to 3 V	0.50	0.10	0.12	0.54	0.92	1.83
3 V to 2 V	0.50	0.10	0.12	0.54	1.05	2.11
2 V to 1 V	0.50	0.10	0.12	0.54	1.18	2.35
1 V to 0.5 V	0.50	0.10	0.12	0.54	1.29	2.57

Table A.4b. Uncertainties, given in μV/V, for the reference TVC build-up at each step from 10 V to 500 V at 10 kHz.

Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 20 V	0.50	0.10	0.12	0.54	0.75	1.50
20 V to 30 V	0.50	0.10	0.12	0.54	0.92	1.83
30 V to 50 V	0.50	0.10	0.12	0.54	1.05	2.11
50 V to 100 V	0.50	0.10	0.12	0.54	1.18	2.35
100 V to 200 V	1.56	0.69	0.52	0.54	2.14	4.27
200 V to 300 V	1.56	0.69	0.52	0.54	2.78	5.56
300 V to 500 V	1.56	0.69	0.52	0.54	3.30	6.61

Table A.5a. Uncertainties, given in μV/V, for the reference TVC build-down at each step from 10 V to 0.5 V at 20 kHz.

Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 5 V	0.52	0.12	0.17	0.60	0.82	1.64
5 V to 3 V	0.52	0.12	0.17	0.60	0.99	1.99
3 V to 2 V	0.52	0.12	0.17	0.60	1.14	2.28
2 V to 1 V	0.52	0.12	0.17	0.60	1.27	2.54
1 V to 0.5 V	0.52	0.12	0.17	0.60	1.39	2.78

Table A.5b. Uncertainties, given in μV/V, for the reference TVC build-up at each step from 10 V to 500 V at 20 kHz.

Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 20 V	0.52	0.12	0.17	0.60	0.82	1.64
20 V to 30 V	0.52	0.12	0.17	0.60	0.99	1.99
30 V to 50 V	0.52	0.12	0.17	0.60	1.14	2.28
50 V to 100 V	0.52	0.12	0.17	0.60	1.27	2.54
100 V to 200 V	1.41	0.87	0.72	0.60	2.21	4.42
200 V to 300 V	1.41	0.87	0.72	0.60	2.85	5.70
300 V to 500 V	1.41	0.87	0.72	0.60	3.38	6.75

Table A.6b. Uncertainties, given in μV/V, for the reference TVC build-down at each step from 10 V to 0.5 V at 50 kHz.						
Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 5 V	0.57	0.14	0.23	0.96	1.15	2.30
5 V to 3 V	0.57	0.14	0.23	0.96	1.31	2.62
3 V to 2 V	0.57	0.14	0.23	0.96	1.45	2.90
2 V to 1 V	0.57	0.14	0.23	0.96	1.58	3.16
1 V to 0.5 V	0.57	0.14	0.23	0.96	1.70	3.40

Table A.6b. Uncertainties, given in μV/V, for the reference TVC build-up at each step from 10 V to 500 V at 50 kHz.						
Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 20 V	0.57	0.13	0.23	0.96	1.15	2.30
20 V to 30 V	0.57	0.13	0.23	0.96	1.31	2.62
30 V to 50 V	0.57	0.13	0.23	0.96	1.45	2.90
50 V to 100 V	0.57	0.13	0.23	0.96	1.58	3.16
100 V to 200 V	1.06	1.04	1.15	0.96	2.46	4.91
200 V to 300 V	1.06	1.04	1.15	0.96	3.09	6.19
300 V to 500 V	1.06	1.04	1.15	0.96	3.62	7.24

Table A.7a. Uncertainties, given in μV/V, for the reference TVC build-down at each step from 10 V to 0.5 V at 100 kHz.						
Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 5 V	0.54	0.29	0.29	1.38	1.53	3.07
5 V to 3 V	0.54	0.29	0.29	1.38	1.68	3.35
3 V to 2 V	0.54	0.29	0.29	1.38	1.81	3.62
2 V to 1 V	0.54	0.29	0.29	1.38	1.93	3.86
1 V to 0.5 V	0.54	0.29	0.29	1.38	2.05	4.09

Table A.7b. Uncertainties, given in μV/V, for the reference TVC build-up at each step from 10 V to 500 V at 100 kHz.						
Voltage Step	S_p (Each step)	$u_{comparator}$ (Each step)	u_{TVC} (Each step)	$u_{reference}$	u_c	U
10 V to 20 V	0.54	0.29	0.40	1.38	1.56	3.12
20 V to 30 V	0.54	0.29	0.40	1.38	1.72	3.45
30 V to 50 V	0.54	0.29	0.40	1.38	1.87	3.75
50 V to 100 V	0.54	0.29	0.40	1.38	2.01	4.02
100 V to 200 V	1.55	1.27	1.67	1.38	3.30	6.59
200 V to 300 V	1.55	1.27	1.67	1.38	4.21	8.41
300 V to 500 V	1.55	1.27	1.67	1.38	4.95	9.90

Appendix B. Uncertainty Analysis for NIST Working Standards

Table B.1. Comparison of working standard F7 set to reference F1 set at 1 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.

Applied Voltage	S_p	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	AC Effects		
0.5 V	0.7	0.2	0.6	0.3	0.6	0.0	0.0	1.1	2.2
1 V	0.6	0.2	0.6	0.3	0.3	0.0	0.0	0.9	1.8
2 V	0.4	0.2	0.6	0.3	0.3	0.0	0.0	0.8	1.6
3 V	0.3	0.2	0.6	0.3	0.3	0.0	0.0	0.8	1.6
5/6 V	0.4	0.2	0.6	0.3	0.3	0.0	0.0	0.8	1.6
10 V	0.5	0.2	0.6	0.3	0.3	0.0	0.0	0.9	1.8
20 V	0.3	0.2	0.9	0.3	0.3	0.0	0.0	1.0	2.0
30 V	0.7	0.2	0.9	0.3	0.3	0.0	0.0	1.2	2.4
50/60 V	0.4	0.2	0.9	0.3	0.3	0.0	0.0	1.1	2.2
100 V	0.6	0.2	0.9	0.3	0.3	0.0	0.0	1.1	2.2
200 V	0.4	0.2	1.2	0.3	0.3	0.3	0.3	1.5	3.0
300 V	0.5	0.2	1.2	0.3	0.6	0.6	0.6	1.7	3.4
500/600 V	0.8	0.2	1.2	0.3	1.2	1.2	1.2	2.5	5.0

Table B.2. Comparison of working standard F7 set to reference F1 set at 10 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.

Applied Voltage	S_p	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	AC Effects		
0.5 V	0.5	0.2	0.6	0.3	0.6	0.0	0.0	1.0	2.0
1 V	0.3	0.2	0.6	0.3	0.3	0.0	0.0	0.8	1.6
2 V	0.7	0.2	0.6	0.3	0.3	0.0	0.0	1.0	2.0
3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.1	2.2
5/6 V	0.7	0.2	0.6	0.3	0.3	0.0	0.0	1.0	2.0
10 V	0.7	0.2	0.6	0.3	0.3	0.0	0.0	1.0	2.0
20 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	1.3	2.5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.0	1.4	2.8
50/60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.0	1.4	2.8
100 V	0.7	0.2	0.9	0.3	0.3	0.0	0.0	1.2	2.4
200 V	0.8	0.2	1.2	0.3	0.3	0.3	0.3	1.6	3.2
300 V	0.8	0.2	1.2	0.3	0.6	0.6	0.6	1.8	3.6
500/600 V	1.1	0.2	1.2	0.3	1.2	1.2	1.2	2.6	5.2

Table B.3. Comparison of working standard F7 set to reference F1 set at 20 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.

Applied Voltage	S_p	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	AC Effects		
0.5 V	0.8	0.2	0.6	0.3	0.6	0.0	0.0	1.2	2.4
1 V	0.9	0.2	0.6	0.3	0.3	0.0	0.0	1.1	2.2
2 V	0.6	0.2	0.6	0.3	0.3	0.0	0.0	1.0	2.0
3 V	0.7	0.2	0.6	0.3	0.3	0.0	0.0	1.0	2.0
5/6 V	1.0	0.2	0.6	0.3	0.3	0.0	0.0	1.2	2.4
10 V	0.7	0.2	0.6	0.3	0.3	0.0	0.0	1.0	2.0
20 V	0.5	0.2	0.9	0.3	0.3	0.0	0.0	1.1	2.2
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.0	1.4	2.8
50/60 V	0.7	0.2	0.9	0.3	0.3	0.0	0.0	1.2	2.4
100 V	0.7	0.2	0.9	0.3	0.3	0.0	0.0	1.2	2.4
200 V	0.8	0.2	1.2	0.3	0.6	0.3	0.3	1.6	3.2
300 V	0.8	0.2	1.2	0.3	0.6	0.6	0.6	1.8	3.6
500/600 V	1.3	0.2	1.2	0.3	1.2	1.2	1.2	2.7	5.4

Table B.4. Comparison of working standard F7 set to reference F1 set at 50 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.

Applied Voltage	S_p	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	AC Effects		
0.5 V	0.7	0.2	0.9	0.3	1.0	0.0	0.5	1.3	2.6
1 V	0.7	0.2	0.9	0.3	0.5	0.0	0.5	1.2	2.4
2 V	0.5	0.2	0.9	0.3	0.5	0.0	0.5	1.1	2.2
3 V	0.9	0.2	0.9	0.3	0.5	0.0	0.5	1.3	2.6
5/6 V	1.0	0.2	0.9	0.3	0.5	0.0	0.5	1.4	2.8
10 V	0.7	0.2	0.9	0.3	0.5	0.0	0.5	1.2	2.4
20 V	0.5	0.2	1.2	0.3	0.5	0.0	0.5	1.4	2.8
30 V	0.5	0.2	1.2	0.3	0.5	0.0	0.5	1.4	2.8
50/60 V	0.8	0.2	1.2	0.3	0.5	0.0	0.5	1.5	3.0
100 V	1.0	0.2	1.2	0.3	0.5	0.0	0.5	1.6	3.2
200 V	1.0	0.2	1.4	0.6	1.0	0.5	1.0	2.1	4.2
300 V	0.9	0.2	1.4	0.6	1.0	1.0	2.0	2.3	4.6
500/600 V	1.2	0.2	1.4	0.6	2.0	2.0	5.0	4.0	8.0

Table B.5. Comparison of working standard F7 set to reference F1 set at 100 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.

Applied Voltage	S_p	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	AC Effects		
0.5 V	1.0	0.2	0.7	0.6	0.6	0.0	0.6	1.8	3.6
1 V	0.9	0.2	0.7	0.6	0.3	0.0	0.6	1.7	3.4
2 V	0.5	0.2	0.7	0.6	0.3	0.0	0.6	1.5	3.0
3 V	0.9	0.2	0.7	0.6	0.3	0.0	0.6	1.7	3.4
5/6 V	0.7	0.2	0.7	0.6	0.3	0.0	0.6	1.6	3.2
10 V	0.6	0.2	0.7	0.6	0.3	0.0	0.6	1.6	3.2
20 V	0.6	0.2	0.7	0.6	0.3	0.0	0.6	2.0	4.0
30 V	0.9	0.2	1.0	0.6	0.3	0.0	0.6	2.1	4.2
50/60 V	0.6	0.2	1.0	0.6	0.3	0.0	0.6	2.0	4.0
100 V	1.1	0.2	1.0	0.6	0.3	0.0	0.6	2.2	4.4
200 V	0.7	0.2	1.7	1.7	0.6	0.4	1.2	3.7	7.4
300 V	0.8	0.2	1.7	1.7	0.6	0.6	1.7	4.0	8.0
500/600 V	1.3	0.2	2.5	2.9	1.2	1.2	4.0	6.9	13.8

Appendix C. Buildup using Working Standards

Table C.1. Working standard F7 set build-up at 1 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.

Voltage Step[2]	S_p (Each Step)	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects		
1 V to 2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.1	2.2
2 V to 3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.5	3.0
3 V to 4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.8	3.6
4 V to 6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.1	4.2
6 V to 10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.4	4.8
10 V to 12 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.7	5.4
12 V to 20 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	2.9	5.8
20 V to 30 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.2	6.4
30 V to 32 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.4	6.8
32 V to 60 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.6	7.2
60 V to 100 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.8	7.6
100 V to 102 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	4.0	8.0
102 V to 200 V	1.0	0.2	0.9	0.3	0.3	0.3	0.3	4.3	8.6
200 V to 300 V	1.2	0.2	1.2	0.3	0.6	0.6	0.6	4.7	9.4
300 V to 302 V	1.2	0.2	1.2	0.3	0.6	0.6	0.6	5.0	10.0
302 V to 600 V	1.5	0.2	1.2	0.3	1.2	1.2	1.2	5.5	11.0
600 V to 1000 V	1.8	0.2	1.2	0.3	1.2	1.2	1.2	6.1	12.2

[2] The uncertainty determined for each step in the build-up or build-down process is calculated by the RSS combination of the uncertainty from the previous step, and the Type A and Type B components of the uncertainty for the measurement of the voltage step being determined. For example, the combined uncertainty for the voltage step from 2 V to 3 V is calculated as: $u_{2Vto3Vstep} = \left(S_0^2 + u_{Detectors}^2 + u_{Sources}^2 + u_{EMI}^2 + u_{Level}^2 + u_{Self-heating}^2 + u_{Ac}^2 + u_{1Vto2Vstep}^2\right)^{1/2}$ or

$u_{2Vto3Vstep} = \left(0.8^2 + 0.2^2 + 0.6^2 + 0.3^2 + 0.3^2 + 1.1^2\right)^{1/2} = 1.5\ \mu V/V$.

Table C.2. Working standard F7 set build-up at 10 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.									
Voltage Step	S_p (Each Step)	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects		
1 V to 2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.1	2.2
2 V to 3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.5	3.0
3 V to 4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.8	3.6
4 V to 6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.1	4.2
6 V to 10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.4	4.8
10 V to 12 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.7	5.4
12 V to 20 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	2.9	5.8
20 V to 30 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.1	6.2
30 V to 32 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.3	6.6
32 V to 60 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.6	7.2
60 V to 100 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.8	7.6
100 V to 102 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	4.0	8.0
102 V to 200 V	1.0	0.2	0.9	0.3	0.3	0.3	0.3	4.2	8.4
200 V to 300 V	1.2	0.2	1.2	0.3	0.6	0.6	0.6	4.6	9.2
300 V to 302 V	1.2	0.2	1.2	0.3	0.6	0.6	0.6	5.0	10.0
302 V to 600 V	1.5	0.2	1.2	0.3	1.2	1.2	1.2	5.5	11.0
600 V to 1000 V	1.8	0.2	1.2	0.3	1.2	1.2	1.2	6.3	12.6

Table C.3. Working standard F7 set build-up at 20 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.									
Voltage Step	S_p (Each Step)	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects		
1 V to 2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.1	2.2
2 V to 3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.5	3.0
3 V to 4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	1.8	3.6
4 V to 6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.1	4.2
6 V to 10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.4	4.8
10 V to 12 V	0.8	0.2	0.6	0.3	0.3	0.0	0.0	2.7	5.5
12 V to 20 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	2.9	5.8
20 V to 30 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.1	6.2
30 V to 32 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.3	6.6
32 V to 60 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.6	7.2
60 V to 100 V	0.8	0.2	0.9	0.3	0.3	0.0	0.0	3.8	7.6
100 V to 102 V	0.8	0.2	0.9	0.3	0.3	0.0	0.5	4.1	8.2
102 V to 200 V	1.0	0.2	0.9	0.3	0.3	0.3	0.3	4.4	8.8
200 V to 300 V	1.2	0.2	1.2	0.3	0.6	0.3	0.3	4.9	9.8
300 V to 302 V	1.2	0.2	1.2	0.3	0.6	0.3	0.3	5.4	10.8
302 V to 600 V	1.5	0.2	1.2	0.3	1.2	0.3	0.3	5.9	11.8
600 V to 1000 V	1.8	0.2	1.2	0.3	1.2	1.2	1.2	6.7	13.4

Table C.4. Working standard F7 set build-up at 50 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.									
Voltage Step	S_p (Each Step)	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects		
1 V to 2 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.3	2.6
2 V to 3 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.8	3.6
3 V to 4 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.2	4.4
4 V to 6 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.5	5.0
6 V to 10 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.8	5.6
10 V to 12 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	3.2	6.4
12 V to 20 V	0.8	0.2	1.2	0.3	0.3	0.0	0.3	3.4	6.8
20 V to 30 V	0.8	0.2	1.2	0.3	0.3	0.0	0.3	3.8	7.6
30 V to 32 V	0.8	0.2	1.2	0.3	0.3	0.0	0.3	4.0	8.0
32 V to 60 V	0.8	0.2	1.2	0.3	0.3	0.0	0.3	4.3	8.6
60 V to 100 V	0.8	0.2	1.2	0.3	0.3	0.0	0.3	4.5	9.0
100 V to 102 V	0.8	0.2	1.2	0.3	0.3	0.0	0.3	4.8	9.6
102 V to 200 V	1.0	0.2	1.2	0.3	0.3	0.3	0.6	5.1	10.2
200 V to 300 V	1.2	0.2	1.4	0.6	0.6	0.3	0.6	5.5	11.0
300 V to 302 V	1.2	0.2	1.4	0.6	0.6	0.3	0.9	6.0	12.0
302 V to 600 V	1.7	0.2	1.4	0.6	1.2	0.6	1.2	6.6	13.2
600 V to 1000 V	1.8	0.2	1.4	0.6	1.2	1.2	1.2	7.3	14.6

Table C.5. Working standard F7 set build-up at 100 kHz. Uncertainties are given in microvolts per volt (μV/V) of applied voltage.									
Voltage Step	S_p (Each Step)	Type B for automated comparator system			Type B for TVCs			u_c	U
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects		
1 V to 2 V	0.8	0.2	0.7	0.6	0.3	0.0	0.6	1.6	3.2
2 V to 3 V	0.8	0.2	0.7	0.6	0.3	0.0	0.6	2.3	4.6
3 V to 4 V	0.8	0.2	0.7	0.6	0.3	0.0	0.6	2.8	5.6
4 V to 6 V	0.8	0.2	0.7	0.6	0.3	0.0	0.6	3.3	6.6
6 V to 10 V	0.8	0.2	0.7	0.6	0.3	0.0	0.6	3.7	7.4
10 V to 12 V	0.8	0.2	0.7	0.6	0.3	0.0	0.6	4.2	8.4
12 V to 20 V	0.8	0.2	1.0	0.6	0.3	0.0	0.6	4.5	9.0
20 V to 30 V	0.8	0.2	1.0	0.6	0.3	0.0	0.6	5.0	10.0
30 V to 32 V	0.8	0.2	1.0	0.6	0.3	0.0	0.6	5.4	10.8
32 V to 60 V	0.8	0.2	1.0	0.6	0.3	0.0	0.6	5.8	11.6
60 V to 100 V	0.8	0.2	1.0	0.6	0.3	0.0	0.6	6.2	12.4
100 V to 102 V	0.8	0.2	1.0	0.6	0.3	0.0	0.6	6.5	13.0
102 V to 200 V	1.0	0.2	1.0	0.6	0.6	0.3	0.9	6.9	13.8
200 V to 300 V	1.2	0.2	1.7	1.7	0.6	0.3	1.2	7.6	15.2
300 V to 302 V	1.2	0.2	1.7	1.7	0.6	0.4	1.2	8.2	16.4
302 V to 600 V	1.7	0.2	2.5	2.9	1.2	0.6	1.7	9.5	19.0
600 V to 1000 V	1.8	0.2	4.0	2.9	1.2	1.2	4.0	11.8	23.6

Table C.6. Final expanded uncertainties for the NIST working standard TVCs from 0.5 V to 1000 V.					
Voltage Range	Expanded Working TVC Uncertainties (k=2)				
	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
0.5 V	3.3	3.3	3.6	4.3	5.5
1 V	2.8	2.8	3.4	4.0	5.1
2 V	1.6	1.8	1.8	2.2	2.9
3 V	1.9	2.1	2.1	2.6	3.3
6 V	2.4	2.5	2.6	3.1	4.0
10 V	2.5	2.6	2.7	3.2	4.2
20 V	3.2	3.2	3.2	3.7	5.2
30 V	3.8	3.5	3.6	4.2	5.7
60 V	3.9	4.0	3.9	4.8	6.4
100 V	4.1	4.1	4.2	5.1	6.9
200 V	5.0	5.0	5.2	6.0	8.5
300 V	5.7	5.7	5.9	6.7	9.5
600 V	6.9	6.9	7.3	8.6	12.8
1000 V	12.1	12.7	13.4	14.7	23.6

Appendix D. Uncertainties For Customer TVCs

Table D.1. Comparison of customer's coaxial TVCs to NIST working standard at 1 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.3	1.6	2.0	5
1 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.4	1.8	4
2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	0.8	1.4	3
3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	0.9	1.5	3
4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.6	4
5 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.6	4
6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.6	4
10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.9	2.4	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.1	2.5	5
120 V	1.2	0.2	1.2	0.3	0.3	0.0	0.3	2.5	3.1	6
200 V	1.2	0.2	1.2	0.3	0.6	0.3	0.6	2.5	3.2	7
300 V	1.2	0.2	1.2	0.3	0.6	0.6	0.6	2.8	3.5	7
400 V	1.2	0.2	1.2	0.3	1.2	1.2	0.9	3.5	4.3	9
500 V	1.2	0.2	1.2	0.3	1.2	1.7	1.2	3.5	4.5	9
600 V	2.0	0.2	1.2	0.3	1.7	2.9	1.2	3.5	5.5	11
1000 V	2.0	0.2	2.3	0.3	1.7	2.9	1.7	6.1	7.6	15

Table D.2. Comparison of customer's coaxial TVCs to NIST working standard at 10 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.3	1.6	2.0	4
1 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.4	1.8	4
2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	0.9	1.4	3
3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.0	1.5	3
4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.7	4
5V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.7	4
6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.7	4
10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.2	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.2	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.8	2.3	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.5	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.5	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.5	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.1	2.5	5
120 V	1.2	0.2	1.2	0.3	0.3	0.0	0.3	2.5	3.1	6
200 V	1.2	0.2	1.2	0.3	0.6	0.3	0.6	2.5	3.2	7
300 V	1.2	0.2	1.2	0.3	0.6	0.6	0.6	2.8	3.5	7
400 V	1.2	0.2	1.2	0.3	1.2	1.2	0.9	3.4	4.3	9
500 V	1.5	0.2	1.2	0.3	1.2	1.7	1.2	3.4	4.6	10
600 V	2.0	0.2	1.2	0.3	1.7	2.9	1.2	3.4	5.5	11
1000 V	2.0	0.2	2.3	0.3	1.7	2.9	1.7	6.3	8.0	16

Table D.3. Comparison of customer's coaxial TVCs to NIST working standard at 20 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.3	1.8	2.1	5
1 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.7	2.0	4
2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	0.9	1.5	3
3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.0	1.6	3
4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
5 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.8	2.3	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.1	2.5	5
120 V	1.5	0.2	1.2	0.3	0.3	0.0	0.3	2.6	3.3	7
200 V	1.5	0.2	1.2	0.3	0.6	0.3	0.6	2.6	3.4	7
300 V	1.5	0.2	1.2	0.3	0.6	0.6	0.6	3.0	3.7	8
400 V	1.5	0.2	1.2	0.3	1.2	1.2	0.9	3.7	4.5	9
500 V	2.0	0.2	1.2	0.3	1.2	1.7	1.2	3.7	5.0	10
600 V	2.2	0.2	1.2	0.3	1.7	2.9	1.2	3.7	5.7	12
1000 V	2.5	0.2	2.3	0.3	1.7	2.9	1.7	6.7	8.4	17

Table D.4. Comparison of customer's coaxial TVCs to NIST working standard at 50 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.5	0.2	0.9	0.3	0.5	0.6	0.6	2.1	2.8	6
1 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	2.0	2.6	5
2 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.1	2.0	4
3 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.3	2.1	4
4 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
5 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
6 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
10 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
12 V	1.5	0.2	0.9	0.3	0.5	0.6	0.6	1.8	2.7	6
20 V	1.5	0.2	1.2	0.3	0.5	0.6	0.6	1.8	2.8	6
30 V	1.5	0.2	1.2	0.3	0.5	0.6	0.6	2.1	3.0	6
40 V	1.5	0.2	1.2	0.3	0.5	0.6	0.6	2.4	3.2	7
50 V	1.5	0.2	1.2	0.3	0.5	0.6	0.6	2.4	3.2	7
60 V	1.5	0.2	1.2	0.3	0.5	0.6	0.6	2.4	3.2	7
100 V	1.5	0.2	1.2	0.3	0.5	0.6	0.6	2.5	3.3	7
120 V	1.8	0.2	1.2	0.6	0.5	0.6	0.6	3.0	3.9	8
200 V	1.8	0.2	1.4	0.6	0.9	1.2	1.2	3.0	4.3	9
300 V	2.0	0.2	1.4	0.6	0.9	1.2	1.2	3.4	4.6	10
400 V	2.0	0.2	1.4	0.6	1.7	1.7	2.3	4.3	6.0	12
500 V	2.2	0.2	1.4	0.6	1.7	2.9	3.5	4.3	7.0	14
600 V	2.2	0.2	1.7	0.6	2.9	2.9	3.5	4.3	7.4	15
1000 V	3.0	0.2	2.9	1.2	2.9	4.0	4.6	7.4	10.9	22

Table D.5. Comparison of customer's coaxial TVCs to NIST working standard at 100 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.8	0.2	1.2	0.6	0.6	0.6	1.2	2.7	3.8	8
1 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	2.6	3.4	7
2 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	1.4	2.7	6
3 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	1.7	2.8	6
4 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	2.0	3.0	6
5 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	2.0	3.0	6
6 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	2.0	3.0	6
10 V	1.2	0.2	1.2	0.6	0.6	0.6	1.2	2.1	3.1	6
12 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	2.6	3.9	8
20 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	2.6	3.9	8
30 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	2.9	4.0	8
40 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	3.2	4.3	9
50 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	3.2	4.3	9
60 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	3.2	4.3	9
100 V	1.7	0.2	1.7	0.6	0.6	0.6	1.2	3.4	4.5	9
120 V	2.0	0.2	2.9	0.6	0.6	0.6	1.2	4.3	5.7	12
200 V	2.0	0.2	2.9	1.7	1.2	1.2	2.9	4.3	6.7	14
300 V	2.3	0.2	2.9	1.7	1.2	1.2	2.9	4.8	7.1	15
400 V	2.3	0.2	4.3	1.7	2.3	2.3	4.3	6.4	9.9	20
500 V	2.5	0.2	4.3	1.7	2.3	3.5	5.2	6.4	10.6	22
600 V	2.5	0.2	4.3	2.9	4.6	3.5	5.2	6.4	11.6	24
1000 V	3.2	0.2	5.8	2.9	5.8	5.2	6.4	11.8	17.1	35

Multirange TVCs using conventional thermoelements

Table D.6. Comparison of customer's multirange TVCs to NIST working standards at 1 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	2.0	0.2	0.6	0.3	0.3	0.0	0.6	1.6	2.8	6
1 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.4	2.0	4
2 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	0.8	1.6	4
3 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	0.9	1.7	4
4 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.2	1.8	4
5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.2	1.8	4
6 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.2	1.8	4
10 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.3	1.9	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.6	2.2	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.6	2.2	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.9	2.4	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.1	2.6	6
120 V	1.5	0.2	1.2	0.3	0.3	0.0	0.6	2.5	3.2	7
200 V	1.5	0.2	1.2	0.3	0.6	0.6	1.2	2.5	3.5	7
300 V	2.0	0.2	1.2	0.3	1.2	1.2	1.7	2.8	4.4	9
400 V	2.0	0.2	1.2	0.3	1.2	2.9	2.9	3.5	6.0	12
500 V	2.0	0.2	1.2	0.3	1.2	2.9	2.9	3.5	6.0	12
600 V	2.5	0.2	1.2	0.3	4.0	4.6	4.0	3.5	8.6	18
1000 V	3.0	0.2	2.3	0.3	4.0	5.8	5.2	6.1	11.1	23

Table D.7. Comparison of customer's multirange TVCs to NIST working standards at 10 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	2.0	0.2	0.6	0.3	0.3	0.0	0.6	1.6	2.8	6
1 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.4	2.0	4
2 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	0.9	1.6	4
3 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.0	1.7	4
4 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.2	1.8	4
5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.2	1.8	4
6 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.2	1.8	4
10 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.3	1.9	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.6	2.2	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.6	2.2	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.8	2.3	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.1	2.6	6
120 V	1.5	0.2	1.2	0.3	0.3	0.0	0.6	2.5	3.2	7
200 V	1.5	0.2	1.2	0.3	0.6	0.6	1.2	2.5	3.5	7
300 V	2.0	0.2	1.2	0.3	1.2	1.2	1.7	2.8	4.4	9
400 V	2.0	0.2	1.2	0.3	1.2	2.9	2.9	3.4	5.9	12
500 V	2.0	0.2	1.2	0.3	1.2	2.9	2.9	3.4	5.9	12
600 V	2.5	0.2	1.2	0.3	4.0	4.6	4.0	3.4	8.6	18
1000 V	3.0	0.2	2.3	0.3	4.0	5.8	5.2	6.3	11.5	23

Table D.8. Comparison of customer's multirange TVCs to NIST working standards at 20 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.5	0.2	0.6	0.3	0.3	0.0	0.6	1.8	2.5	5
1 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.7	2.2	5
2 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	0.9	1.6	4
3 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.0	1.7	4
4 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.3	1.9	4
5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.3	1.9	4
6 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.3	1.9	4
10 V	1.0	0.2	0.6	0.3	0.3	0.0	0.6	1.3	1.9	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.6	2.2	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.6	2.2	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	1.8	2.3	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.0	2.5	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.6	2.1	2.6	6
120 V	1.5	0.2	1.2	0.3	0.3	0.0	0.6	2.6	3.3	7
200 V	1.5	0.2	1.2	0.3	0.6	0.6	1.2	2.6	3.5	8
300 V	2.0	0.2	1.2	0.3	1.2	1.2	1.7	3.0	4.5	9
400 V	2.0	0.2	1.2	0.3	1.2	2.9	2.9	3.7	6.1	13
500 V	2.5	0.2	1.2	0.3	1.2	2.9	2.9	3.7	6.3	13
600 V	3.0	0.2	1.2	0.3	4.0	4.6	4.0	3.7	8.8	18
1000 V	3.5	0.2	2.3	0.3	4.0	5.8	5.2	6.7	11.8	24

Table D.9. Comparison of customer's multirange TVCs to NIST working standards at 50 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	2.0	0.2	0.9	0.3	1.2	0.6	1.2	2.1	3.3	7
1 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	2.0	3.0	6
2 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	1.1	2.5	5
3 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	1.3	2.6	5
4 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	1.6	2.7	6
5 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	1.6	2.7	6
6 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	1.6	2.7	6
10 V	1.5	0.2	0.9	0.3	1.2	0.6	1.2	1.6	2.8	6
12 V	1.8	0.2	0.9	0.3	1.2	0.6	1.2	1.8	3.1	7
20 V	1.8	0.2	1.2	0.3	1.2	0.6	1.2	1.8	3.1	7
30 V	1.8	0.2	1.2	0.3	1.2	0.6	1.2	2.1	3.3	7
40 V	1.8	0.2	1.2	0.3	1.2	0.6	1.2	2.4	3.5	7
50 V	1.8	0.2	1.2	0.3	1.2	0.6	1.2	2.4	3.5	7
60 V	1.8	0.2	1.2	0.3	1.2	0.6	1.2	2.4	3.5	7
100 V	1.8	0.2	1.2	0.3	1.2	0.6	1.2	2.5	3.6	7
120 V	2.0	0.2	1.2	0.6	1.2	0.6	1.2	3.0	4.1	8
200 V	2.0	0.2	1.4	0.6	1.7	1.2	1.7	3.0	4.5	9
300 V	2.5	0.2	1.4	0.6	2.3	1.2	2.3	3.4	5.3	11
400 V	2.5	0.2	1.4	0.6	3.5	2.9	3.5	4.3	7.1	15
500 V	2.5	0.2	1.4	0.6	3.5	2.9	3.5	4.3	7.5	15
600 V	2.5	0.2	1.7	0.6	5.8	4.6	5.8	4.3	10.8	22
1000 V	3.0	0.2	2.9	1.2	7.5	6.4	7.5	7.4	15.1	31

Table D.10. Comparison of customer's multirange TVCs to NIST working standards at 100 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	2.0	0.2	1.2	0.6	0.6	0.6	2.9	2.7	4.7	10
1 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	2.6	4.5	9
2 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	1.4	4.0	8
3 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	1.7	4.1	8
4 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	2.0	4.2	9
5 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	2.0	4.2	9
6 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	2.0	4.2	9
10 V	1.8	0.2	1.2	0.6	0.6	0.6	2.9	2.1	4.3	10
12 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	2.6	4.8	10
20 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	2.6	4.8	10
30 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	2.9	4.9	10
40 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	3.2	5.2	11
50 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	3.2	5.2	11
60 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	3.2	5.2	11
100 V	2.0	0.2	1.7	0.6	0.6	0.6	2.9	3.4	5.3	11
120 V	2.5	0.2	2.9	0.6	0.6	0.6	2.9	4.3	6.5	13
200 V	2.5	0.2	2.9	1.7	1.2	1.2	2.9	4.3	6.8	14
300 V	2.8	0.2	2.9	1.7	1.2	2.9	2.9	4.8	7.7	16
400 V	2.8	0.2	4.3	1.7	2.9	4.6	4.3	6.4	10.9	22
500 V	3.0	0.2	4.3	1.7	2.9	4.6	5.8	6.4	11.6	24
600 V	3.0	0.2	4.3	2.9	6.9	8.7	8.7	6.4	16.6	34
1000 V	4.0	0.2	5.8	2.9	8.7	11.5	10.4	11.8	22.7	46

Multirange TVCs with Solid-State Circuit Elements as Thermal Sensors

Table D.11. Comparison of customer's multirange TVCs to NIST working standards at 1 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.3	1.6	2.1	4
1 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.4	1.8	4
2 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	0.8	1.2	3
3 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	0.9	1.3	3
4 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.5	3
5 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.5	3
6 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.5	3
10 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.6	3
12 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	4
20 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	4
30 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.9	2.3	5
40 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.3	5
50 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.3	5
60 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.3	5
100 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.1	2.4	5
120 V	1.0	0.2	1.2	0.3	0.3	0.0	0.3	2.5	3.0	6
200 V	1.0	0.2	1.2	0.3	0.6	0.3	0.6	2.5	3.1	7
300 V	1.2	0.2	1.2	0.3	1.2	0.6	0.6	2.8	3.6	8
400 V	1.2	0.2	1.2	0.3	1.2	1.2	0.9	3.5	4.3	9
500 V	1.2	0.2	1.2	0.3	1.2	1.7	1.2	3.5	4.5	9
600 V	1.5	0.2	1.2	0.3	1.7	1.7	1.2	3.5	4.8	10
1000 V	1.5	0.2	2.3	0.3	1.7	2.9	1.7	6.1	7.4	15

Table D.12. Comparison of customer's multirange TVCs to NIST working standards at 10 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.3	1.6	2.1	4
1 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.4	1.8	4
2 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	0.9	1.3	3
3 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.0	1.4	3
4 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.5	3
5 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.5	3
6 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.2	1.5	3
10 V	0.5	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.6	3
12 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	4
20 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	4
30 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	1.8	2.2	5
40 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
50 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
60 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	6
100 V	0.8	0.2	0.9	0.3	0.3	0.0	0.3	2.1	2.4	6
120 V	1.0	0.2	1.2	0.3	0.3	0.0	0.3	2.5	3.0	6
200 V	1.0	0.2	1.2	0.3	0.6	0.3	0.6	2.5	3.1	6
300 V	1.2	0.2	1.2	0.3	1.2	0.6	0.6	2.8	3.6	8
400 V	1.2	0.2	1.2	0.3	1.2	1.2	0.9	3.4	4.3	9
500 V	1.2	0.2	1.2	0.3	1.2	1.7	1.2	3.4	4.5	9
600 V	1.5	0.2	1.2	0.3	1.7	1.7	1.2	3.4	4.8	10
1000 V	1.5	0.2	2.3	0.3	1.7	2.9	1.7	6.3	7.9	16

Table D.13. Comparison of customer's multirange TVCs to NIST working standards at 20 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.0	0.2	0.6	0.3	0.3	0.0	0.3	1.8	2.1	4
1 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.7	2.0	4
2 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	0.9	1.4	3
3 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.0	1.5	3
4 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
5 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
6 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
10 V	0.8	0.2	0.6	0.3	0.3	0.0	0.3	1.3	1.7	4
12 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	5
20 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.6	2.1	5
30 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	1.8	2.3	5
40 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
50 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
60 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.0	2.4	5
100 V	1.0	0.2	0.9	0.3	0.3	0.0	0.3	2.1	2.5	5
120 V	1.2	0.2	1.2	0.3	0.3	0.0	0.3	2.6	3.1	7
200 V	1.2	0.2	1.2	0.3	0.6	0.3	0.6	2.6	3.2	7
300 V	1.2	0.2	1.2	0.3	1.2	0.6	0.6	3.0	3.7	8
400 V	1.2	0.2	1.2	0.3	1.2	1.2	0.9	3.7	4.4	9
500 V	1.5	0.2	1.2	0.3	1.2	1.7	1.2	3.7	4.8	10
600 V	1.5	0.2	1.2	0.3	1.7	1.7	1.2	3.7	4.9	10
1000 V	2.0	0.2	2.3	0.3	1.7	2.9	1.7	6.7	8.3	17

Table D.14. Comparison of customer's multirange TVCs to NIST working standards at 50 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.5	0.2	0.9	0.3	0.5	0.6	0.6	2.1	2.8	6
1 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	2.0	2.6	6
2 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.1	2.0	4
3 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.3	2.1	4
4 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
5 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
6 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
10 V	1.0	0.2	0.9	0.3	0.5	0.6	0.6	1.6	2.3	5
12 V	1.2	0.2	0.9	0.3	0.5	0.6	0.6	1.8	2.6	6
20 V	1.2	0.2	1.2	0.3	0.5	0.6	0.6	1.8	2.7	6
30 V	1.2	0.2	1.2	0.3	0.5	0.6	0.6	2.1	2.9	6
40 V	1.2	0.2	1.2	0.3	0.5	0.6	0.6	2.4	3.1	7
50 V	1.2	0.2	1.2	0.3	0.5	0.6	0.6	2.4	3.1	7
60 V	1.2	0.2	1.2	0.3	0.5	0.6	0.6	2.4	3.1	7
100 V	1.2	0.2	1.2	0.3	0.5	0.6	0.6	2.5	3.2	7
120 V	1.5	0.2	1.2	0.6	0.5	0.6	0.6	3.0	3.7	8
200 V	1.5	0.2	1.4	0.6	0.9	1.2	0.6	3.0	4.0	8
300 V	1.8	0.2	1.4	0.6	1.7	1.2	0.9	3.4	4.7	10
400 V	1.8	0.2	1.4	0.6	1.7	1.7	1.2	4.3	5.6	12
500 V	2.0	0.2	1.4	0.6	2.3	2.9	2.9	4.3	6.8	14
600 V	2.0	0.2	1.7	0.6	2.9	2.9	2.9	4.3	7.1	15
1000 V	2.5	0.2	2.9	1.2	4.3	4.0	4.0	7.4	11.0	22

Table D.15. Comparison of customer's multirange TVCs to NIST working standards at 100 kHz. The assigned uncertainty is the expanded (k = 2) uncertainty provided to the customer, in μV/V.

Applied Voltage	Pooled standard deviation	Type B for automated comparator system			Type B for TVCs			Working Standard Uncertainty	u_c	Assigned Uncertainty
		Detectors	Sources	EMI effects	Level Coefficient	Self-heating	Ac Effects			
0.5 V	1.8	0.2	1.2	0.6	0.6	0.6	0.9	2.7	3.7	8
1 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	2.6	3.3	7
2 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	1.4	2.6	5
3 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	1.7	2.7	6
4 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	2.0	2.9	6
5 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	2.0	2.9	6
6 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	2.0	2.9	6
10 V	1.2	0.2	1.2	0.6	0.6	0.6	0.9	2.1	3.0	6
12 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	2.6	3.7	8
20 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	2.6	3.7	8
30 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	2.9	3.9	8
40 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	3.2	4.2	9
50 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	3.2	4.2	9
60 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	3.2	4.2	9
100 V	1.5	0.2	1.7	0.6	0.6	0.6	0.9	3.4	4.3	9
120 V	1.8	0.2	2.9	0.6	0.6	0.6	0.9	4.3	5.6	12
200 V	1.8	0.2	2.9	1.7	1.2	1.2	0.9	4.3	6.0	12
300 V	2.0	0.2	2.9	1.7	2.3	1.2	1.2	4.8	6.8	14
400 V	2.0	0.2	4.3	1.7	2.3	1.4	2.0	6.4	8.8	18
500 V	2.2	0.2	4.3	1.7	3.5	2.9	4.3	6.4	10.3	21
600 V	2.2	0.2	4.3	2.9	4.6	2.9	4.3	6.4	11.0	22
1000 V	2.8	0.2	5.8	2.9	5.8	5.2	5.8	11.8	16.8	34

Appendix E. Uncertainties For NIST Standards at Frequencies above 100 kHz

Table E.1 contains the uncertainty contributions for the specially constructed 5 V to 20 V TVCs. The uncertainty elements include: primary standards, stability of lower frequency TVCs, comparator system for lower frequency measurements, low frequency voltage steps, thermoelement as current comparator, transimpedance of resistor, current standing wave, tee and connector voltage standing wave, connector reproducibility, lower frequency extension, skin effect, and high frequency comparator system.

Table E.1. Uncertainties for the specially constructed 5 V – 20 V TVCs in μV/V.

	200 kHz	500 kHz	700 kHz	1 MHz
Type A standard uncertainty	0.80	0.80	0.80	0.80
Type B contributions				
Primary standard MJTCs	0.29	0.29	0.29	0.29
Stability of standards	0.23	0.23	0.23	0.23
Comparator system for transfer to reference TVC	0.23	0.23	0.23	0.23
Voltage step-up, each step	0.23	0.23	0.23	0.23
Two steps	0.23	0.23	0.23	0.23
Thermoelement model	1.44	1.73	2.31	3.18
Transimpedance of resistor	1.15	1.73	3.18	5.20
Current standing wave	1.15	1.73	3.18	5.20
Tee and connector standing wave ratio	1.15	1.73	1.73	3.18
Connector reproducibility	1.15	1.44	1.73	3.46
Frequency extension	1.44	1.73	2.31	3.18
Skin effect	1.15	1.44	1.73	3.18
Comparator system	2.31	2.31	2.31	2.31
Combined Uncertainty	4.14	5.04	6.79	10.61

The uncertainty contributions associated with the build-up and build-down processes for the higher and lower voltage TVCs in the frequency range from 200 kHz to 1 MHz are given in Tables E.2 and E.3. The elements include elements due to the comparator and level dependence of the TVCs.

Table E.2. Uncertainties For NIST Standards

Voltage Level	200 kHz build-up and build-down from the 5 V – 20 V high-frequency reference standards					500 kHz build-up and build-down from the 5 V – 20 V high-frequency reference standards				
	Type A	Comparator	Level De-pendance	Previous	u_c	Type A	Comparator	Level De-pendance	Previous	u_c
100 V	1.0	2.3	2.3	4.9	6.0	1.0	2.3	2.3	5.8	6.7
50 V	1.0	2.3	1.2	4.1	4.9	1.0	2.3	1.4	5.0	5.8
3 V	1.0	2.3	1.2	4.1	4.9	1.0	2.3	1.4	5.0	5.8
2 V	1.0	2.3	1.2	4.9	5.6	1.0	2.3	1.4	5.8	6.4
1 V	1.0	2.3	1.2	5.6	6.2	1.0	2.3	1.4	6.4	7.0
0.5 V	1.0	2.3	1.2	6.2	6.8	1.0	2.3	1.4	7.0	7.6

Table E.3. Uncertainties For NIST Standards

Voltage Level	700 kHz build-up and build-down from the 5 V – 20 V high-frequency reference standards					1 MHz build-up and build-down from the 5 V – 20 V high-frequency reference standards				
	Type A	Comparator	Level De-pendance	Previous	u_c	Type A	Comparator	Level De-pendance	Previous	u_c
100 V	1.0	2.3	3.5	7.6	8.7	1.0	2.3	5.2	11.3	12.7
50 V	1.0	2.3	2.3	6.8	7.6	1.0	2.3	3.2	10.6	11.3
3 V	1.0	2.3	2.3	6.8	7.6	1.0	2.3	3.2	10.6	11.3
2 V	1.0	2.3	2.3	7.6	8.3	1.0	2.3	3.2	11.3	12.0
1 V	1.0	2.3	2.3	8.3	9.0	1.0	2.3	3.2	12.0	12.7
0.5 V	1.0	2.3	2.3	8.9	9.6	1.0	2.3	3.2	12.7	13.3

Appendix F. Uncertainties For Customer TVCs At Frequencies above 100 kHz

All ac-dc difference uncertainties reported in this document are given in microvolts per volt (μV/V) of applied voltage.

Table F.1. Customer TVCs at 200 kHz

Applied Voltage	S_p	Detectors	Sources	EMI effects	Level coefficient	Self-heating	AC effects	NIST Standard	u_c	Assigned Uncertainty
0.5	1.0	0.4	4.0	2.0	2.0	1.0	5.0	6.9	10.0	20
1	1.0	0.4	4.0	2.0	2.0	1.0	5.0	6.3	9.6	10
2	1.0	0.4	4.0	2.0	2.0	1.0	5.0	5.7	9.1	18
3	1.0	0.4	4.0	2.0	2.0	1.0	5.0	5.0	8.7	18
5	1.0	0.4	4.0	2.0	2.0	1.0	5.0	4.1	8.3	17
10	1.0	0.4	4.0	2.0	2.0	1.0	5.0	4.1	8.3	17
20	1.0	0.4	4.0	2.0	2.0	1.0	5.0	4.1	8.3	17
30	1.0	0.4	6.0	2.0	2.0	1.0	5.0	5.0	9.8	20
50	1.0	0.4	6.0	2.0	2.0	1.0	5.0	5.0	9.8	20
100	1.0	0.4	6.0	2.0	2.0	1.0	5.0	6.0	10.4	21

Table F.2. Customer TVCs at 500 kHz

Applied Voltage	S_p	Detectors	Sources	EMI effects	Level coefficient	Self-heating	AC effects	NIST Standard	u_c	Assigned Uncertainty
0.5	1.0	0.4	4.0	2.0	2.0	1.0	6.0	7.7	11.0	22
1	1.0	0.4	4.0	2.0	2.0	1.0	6.0	7.1	10.6	21
2	1.0	0.4	4.0	2.0	2.0	1.0	6.0	6.5	10.2	21
3	1.0	0.4	4.0	2.0	2.0	1.0	6.0	5.8	9.8	20
5	1.0	0.4	4.0	2.0	2.0	1.0	6.0	5.0	9.4	19
10	1.0	0.4	4.0	2.0	2.0	1.0	6.0	5.0	9.4	19
20	1.0	0.4	4.0	2.0	2.0	1.0	6.0	5.0	9.4	19
30	1.0	0.4	6.0	2.0	2.0	1.0	6.0	5.8	10.8	22
50	1.0	0.4	6.0	2.0	2.0	1.0	6.0	5.8	10.8	22
100	1.0	0.4	6.0	2.0	2.0	1.0	6.0	6.8	11.3	23

Table F.3. Customer TVCs at 700 kHz										
Applied Voltage	S_p	Detectors	Sources	EMI effects	Level coefficient	Self-heating	AC effects	NIST Standard	u_c	Assigned Uncertainty
0.5	1.0	0.4	4.0	2.0	2.0	1.0	7.0	9.6	13.0	26
1	1.0	0.4	4.0	2.0	2.0	1.0	7.0	9.0	12.5	25
2	1.0	0.4	4.0	2.0	2.0	1.0	7.0	8.3	12.0	24
3	1.0	0.4	4.0	2.0	2.0	1.0	7.0	7.6	11.5	23
5	1.0	0.4	4.0	2.0	2.0	1.0	7.0	6.8	11.0	22
10	1.0	0.4	4.0	2.0	2.0	1.0	7.0	6.8	11.0	22
20	1.0	0.4	4.0	2.0	2.0	1.0	7.0	6.8	11.0	22
30	1.0	0.4	6.0	2.0	2.0	1.0	7.0	7.6	12.4	25
50	1.0	0.4	6.0	2.0	2.0	1.0	7.0	7.6	12.4	25
100	1.0	0.4	6.0	2.0	2.0	1.0	7.0	8.7	13.1	26

Table F.4. Customer TVCs at 1 MHz										
Applied Voltage	S_p	Detectors	Sources	EMI effects	Level coefficient	Self-heating	AC effects	NIST Standard	u_c	Assigned Uncertainty
0.5	1.0	0.4	4.0	2.0	2.0	1.0	8.0	13.4	16.4	33
1	1.0	0.4	4.0	2.0	2.0	1.0	8.0	12.7	15.8	32
2	1.0	0.4	4.0	2.0	2.0	1.0	8.0	12.1	15.4	31
3	1.0	0.4	4.0	2.0	2.0	1.0	8.0	11.4	14.8	30
5	1.0	0.4	4.0	2.0	2.0	1.0	8.0	10.6	14.2	28
10	1.0	0.4	4.0	2.0	2.0	1.0	8.0	10.6	14.2	28
20	1.0	0.4	4.0	2.0	2.0	1.0	8.0	10.6	14.2	28
30	1.0	0.4	6.0	2.0	2.0	1.0	8.0	11.4	15.5	31
50	1.0	0.4	6.0	2.0	2.0	1.0	8.0	11.4	15.5	31
100	1.0	0.4	6.0	2.0	2.0	1.0	8.0	12.7	16.5	33

Appendix G. Summary of Assigned Uncertainties for Customer's TVCs

Table G.1. Assigned uncertainty, in μV/V, for customer's coaxial standards. For applied frequencies and voltages between those listed, the smaller uncertainty applies. The shaded region is not routinely offered as part of the calibration service.

Applied Voltage	Uncertainty in μV/V of applied voltage													
V	10 Hz	20 Hz	40 Hz	100 Hz	400 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	200 kHz	500 kHz	700 kHz	1 MHz
0.5	13	11	9	5	5	5	4	5	6	8	20	22	26	33
1	14	11	9	5	5	4	4	4	5	7	19	22	25	32
2	14	11	9	5	5	3	3	3	4	6	19	21	24	31
3	14	12	10	5	5	3	3	3	4	6	18	20	23	30
4	14	12	10	5	5	4	4	4	5	6	18	20	23	30
5	15	12	10	5	5	4	4	4	5	6	17	19	22	29
6	15	12	10	5	5	4	4	4	5	6	17	19	22	29
10	15	12	10	5	5	4	4	4	5	6	17	19	22	29
12	15	12	10	5	5	5	5	5	6	8	17	19	22	29
20	16	12	10	5	5	5	5	5	6	8	17	19	22	29
30	16	13	10	6	5	5	5	5	6	8	20	22	22	31
40	16	13	10	6	5	5	5	5	7	9	20	22	25	31
50	17	13	11	6	5	5	5	5	7	9	20	22	25	31
60	17	13	11	6	6	5	5	5	7	9	20	22	25	31
100	17	13	11	6	6	5	5	5	7	9	21	23	27	33
120	100	20	20	20	20	6	6	7	8	12				
200	100	20	20	20	20	7	7	7	9	14				
300	100	20	20	20	20	7	7	8	10	15				
400	100	20	20	20	20	9	9	9	12	20				
500	100	20	20	20	20	9	10	10	14	22				
600	100	20	20	20	20	11	11	12	15	24				
1000	100	20	20	20	20	15	16	17	22	35				

Table G.2. Assigned uncertainty, in μV/V, for customer's multirange transfer standards that use a solid-state sensor. For applied frequencies and voltages between those listed, the smaller uncertainty applies. The shaded region is not routinely offered as part of the calibration service.

Applied Voltage	Uncertainty in μV/V of applied voltage													
V	10 Hz	20 Hz	40 Hz	100 Hz	400 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	200 kHz	500 kHz	700 kHz	1 MHz
0.5	21	17	16	6	5	4	4	4	6	8	20	22	26	33
1	21	18	16	6	5	4	4	4	6	7	19	22	25	32
2	21	18	16	6	5	3	3	3	4	5	19	21	24	31
3	22	18	16	6	5	3	3	3	4	6	18	20	23	30
4	22	18	16	6	5	3	3	4	5	6	18	20	23	30
5	22	18	16	6	5	3	3	4	5	6	17	19	22	29
6	22	18	16	6	6	3	3	4	5	6	17	19	22	29
10	22	18	16	6	6	3	3	4	5	6	17	19	22	29
12	22	18	16	6	6	4	4	5	6	8	17	19	22	29
20	22	19	16	6	6	4	4	5	6	8	17	19	22	29
30	23	19	17	6	6	5	5	5	6	8	20	22	22	31
40	23	19	17	6	6	5	5	5	7	9	20	22	25	31
50	23	19	17	6	6	5	5	5	7	9	20	22	25	31
60	23	19	17	6	6	5	6	5	7	9	20	22	25	31
100	23	19	17	6	6	5	6	5	7	9	21	23	27	33
120	100	20	20	20	20	6	6	7	8	12				
200	100	20	20	20	20	7	6	7	8	12				
300	100	20	20	20	20	8	8	8	10	14				
400	100	20	20	20	20	9	9	9	12	18				
500	100	20	20	20	20	9	9	10	14	21				
600	100	20	20	20	20	10	10	10	15	22				
1000	100	20	20	20	20	15	16	17	22	34				

Table G.3. Assigned uncertainty, in μV/V, for customer's multirange transfer standards that use a conventional thermoelement. For applied frequencies and voltages between those listed, the smaller uncertainty applies. The shaded region is not routinely offered as part of the calibration service.

Applied Voltage	Uncertainty in μV/V of applied voltage													
V	10 Hz	20 Hz	40 Hz	100 Hz	400 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	200 kHz	500 kHz	700 kHz	1 MHz
0.5	14	12	11	10	10	6	6	5	7	10	20	22	26	33
1	14	13	12	10	10	4	4	5	6	9	19	22	25	32
2	15	13	12	10	10	4	4	4	5	8	19	21	24	31
3	15	14	13	10	10	4	4	4	5	8	18	20	23	30
4	15	14	13	10	10	4	4	4	6	9	18	20	23	30
5	15	14	13	10	10	4	4	4	6	9	17	19	22	29
6	16	14	13	10	10	4	4	4	6	9	17	19	22	29
10	16	15	14	11	10	4	4	4	6	10	17	19	22	29
12	16	15	14	11	10	5	5	5	7	10	17	19	22	29
20	16	15	14	11	10	5	5	5	7	10	17	19	22	29
30	17	15	15	11	10	5	5	5	7	10	20	22	22	31
40	17	15	15	11	10	5	5	5	7	11	20	22	25	31
50	17	15	15	11	10	5	5	5	7	11	20	22	25	31
60	17	16	15	11	10	5	5	5	7	11	20	22	25	31
100	18	16	15	11	10	6	6	6	7	11	21	23	27	33
120	100	20	20	20	20	7	7	7	8	13				
200	100	20	20	20	20	7	7	8	9	14				
300	100	20	20	20	20	9	9	9	11	16				
400	100	20	20	20	20	12	12	13	15	22				
500	100	20	20	20	20	12	12	13	15	24				
600	100	20	20	20	20	18	18	18	22	34				
1000	100	20	20	20	20	23	23	24	31	46				